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Kinetically Stabilized Axisymmetric Tandem Mirrors: Summary of Studies

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Richard F. Post, Principal Investigator

**Kinetically Stabilized Axisymmetric Tandem Mirrors:
Summary of Studies**

The path to practical fusion power through plasma confinement in magnetic fields, if it is solely based on the present front-runner, the tokamak, is clearly long, expensive, and arduous. The root causes for this situation lie in the effects of endemic plasma turbulence and in the complexity the tokamak's "closed" field geometry. The studies carried out in the investigations described in the attached reports are aimed at finding an approach that does not suffer from these problems. This goal is to be achieved by employing an axisymmetric "open" magnetic field geometry, i.e. one generated by a linear array of circular magnet coils, and employing the magnetic mirror effect in accomplishing the plugging of end leakage. More specifically, the studies were aimed at utilizing the tandem-mirror concept [1,2] in an axisymmetric configuration to achieve performance superior to the tokamak, and in a far simpler system, one for which the cost and development time could be much lower than that for the tokamak, as exemplified by ITER and its follow-ons.

An important stimulus for investigating axisymmetric versions of the tandem mirror is the fact that, beginning from early days in fusion research there have been examples of axisymmetric mirror experiments [3,4,5] where the plasma exhibited cross-field transport far below the turbulence-enhanced rates characteristic of tokamaks, in specific cases approaching the "classical" rate. From the standpoint of theory, axisymmetric mirror-based systems have special characteristics that help explain the low levels of turbulence that have been observed. Among these are the facts that there are no parallel currents in the equilibrium state, and that the drift surfaces of all of the trapped particles are closed surfaces, as shown early on by Teller and Northrop [6]. In addition, in such systems it is possible to arrange that the radial boundary of the confined plasma terminates without contact with the chamber wall. This possibility reduces the probability of so-called "temperature-gradient" instabilities, known to be endemic to closed systems. Finally, the open-ended nature of the field readily allows the control of the radial potential distribution, a circumstance that has been shown, for example in the Gamma 10 tandem-mirror experiment [7] at Tsukuba Japan, to suppress drift-type instability modes.

Standing against all of these attractive properties of axisymmetric mirror-based systems is the fact, shown early on [8], that such systems are prone to MHD "interchange" instabilities, one in which the plasma column drifts transversely, at a rate far above classical transport. Observed early on, the "cure" that was universally adopted, as first demonstrated in the famous "Ioffe experiment [9], was to abandon axisymmetry and employ so-called "magnetic-well" fields, ones in which the field increases radially and axially from its interior, strongly suppressing the MHD interchange

mode, up to plasma “beta” values approaching unity, observed in the 2X2B experiment [10]. When the tandem mirror concept was introduced in 1976 every experiment that was constructed employed various combinations of non-axisymmetric coil configurations (“Baseball,” and “Yin-Yang” [11] coils) to create the magnetic fields. But it came at a heavy price: non-axisymmetric fields gave rise to new non-classical loss channels, and the complexity of the fields introduced difficult engineering problems. It was well recognized at the time that it would be highly advantageous to preserve axisymmetry of the tandem mirror coils, but there was no apparent way to stabilize the ubiquitous MHD interchange mode.

A decade later a way to accomplish this end was analyzed theoretically, and, a few years later successfully demonstrated experimentally, in the Gas Dynamic Trap (GDT) experiment [12] at Novosibirsk. The concept: the presence of a sufficient amount of plasma on the expanding field lines outside the end mirrors of a mirror machine can act as an “anchor,” MHD stabilizing the interior, confined, plasma. Moreover, Ryutov’s theory showed that the pressure of this anchor plasma could be orders of magnitude smaller than that of the confined plasma, and still be able to stabilize it. In the GDT, which operates in a collision-dominated region (as opposed to the near-collisionless mode of a tandem mirror), the effluent plasma, though much lower in density than that of the confined plasma, is sufficient to stabilize the central plasma, up to plasma beta values of 40 percent. Furthermore, once MHD stabilized, the confined plasma in the GDT exhibited no signs of plasma turbulence or enhanced cross-field transport, even in the presence of a substantial population of high energy ions produced by neutral-beam injection.

The Kinetic Stabilizer (K-S) represents a means of implementing Ryutov’s stabilization concept in low-collisionality regimes, where the effluent flux in the expander regions is too low for his technique to operate. In the K-S’s simplest form it is based on the use of ion beams, injected inward at small angles to the field line directions at the end of the expander. These ions, compressed, stagnated, and reflected within the expander, together with their accompanying electrons form the “Kinetic Stabilizer” plasma. The studies we have done of this concept, briefly summarized below, are described in detail in the accompanying reports. These reports represent both refereed publications and internal reports. Taken together they represent the chronological sequence in which the K-S studies were made

Summary of results

In the studies described in the reports several computer codes, both newly written ones, and “legacy” codes developed in the 1980’s in the LLNL mirror program, were employed. One of the most useful codes for, valid for low-beta “scoping” and injection optimization studies, was based on the Mathematica[®] platform. Another code, the legacy code, FLORA [13] is an MHD-stability code. This code was upgraded so that it can be run on present-day computer systems. The results of FLORA code calculations are valid at high beta. This code was first benchmarked against the Mathematica code, and then used to extend its results into high-beta regimes. A third code, SYMTRAN [14] by Fowler and Hua, was especially written to analyze the radial transport in axisymmetric tandem mirror systems, including the radial distribution of the potential in

the “plugs” and the central cell. This code predicts D-T ignition and stable burn at plasma radii and confining fields much lower than those projected for igniting tokamak systems.

The starting point for the analysis, as it was programmed using the Mathematica[®] platform, is the equation employed by Ryutov in his analysis, a pressure-weighted MHD stability integral. This integral, integrated over a given flux line from one end of that flux line (at the outer end of one expander, all the way to the outer end of the expander at the other end of the machine. The integrand is expressed in terms of the plasma radius and the total plasma pressure at every position along the line from one end of the system to the other. If the value of this integral is positive the flux surface along which the integral is evaluated is assured to be stable against MHD instability modes. If the condition is satisfied on all flux surfaces on which plasma lies, the plasma column itself is assured MHD stable, at least at low beta values.

Stated in the form of an inequality, the stability integral takes the form:

$$I_s = \int_L^L a^3 \frac{d^3 a}{dz^3} \{p_\perp + p_\parallel + \frac{1}{2} v^2\} dz > 0, \text{ Stable} \quad [1]$$

In the expander region the curvature derivative, $d^3 a/dz^3$, is positive and typically larger than the negative-values of that derivative in the confining cell. Furthermore, in the region of the expander that lies well beyond the outer mirror throat, the value of the plasma radius, a , will typically be much larger than its corresponding values in the mirror confinement cells. It follows from the a^3 scaling of the integrand that a high plasma pressure in the confinement regions can be MHD stabilized by a much lower pressure located in the expander. In fact it was found that by carefully tailoring both the shape of the expander flux lines and the K-S ion injection angular distribution at the end of the expander that the stabilization effect could be optimized, to the point that the pressure of the beam-created stabilizing plasma could be many orders of magnitude smaller than that of the confined plasma, requiring K-S ion beam powers that were very small compared to the fusion power release in a typical case. These observations as to the small amount of plasma required to stabilize a high pressure plasma were confirmed in the GDT, where it was shown by direct experimental tests involving perturbing the expander field line shaper that the plasma at the outer, larger radius, portion of the expander region was most effective in MHD-stabilizing.

While the code based on the Mathematica[®] platform was found to be an effective way of optimizing expander flux configurations and K-S ion-beam injection angular distributions, for results valid at high beta values we relied on the FLORA code. This code, written at LLNL in the 1980's required a substantial amount of reworking to enable it to be used on present-day operating systems. Once debugged, it performed very well. When benchmarked at low beta with the Mathematica[®]-based code it gave almost identical results.

Using FLORA MHD-stable cases were found with central beta values as high as 40 percent, stable not only against the interchange mode but also the “firehose” and “mirror” modes. An example of such a case is shown in one of the attached reports.

In addition to the MHD stability code calculations, substantial effort was put into finding optimized shapes for the expander fields, together with optimized K-S ion injected ion distributions. When these optimizations were made, performance improvements of as much as an order-of-magnitude were found. In addition to these optimizations, alternate modes of operation were explored, these included the possible use of gas jets injected on the outer part of the outermost mirrors. The concept was the following one: K-S ion injection would be used initially to allow a stable build-up of the tandem-mirror plug and central-cell plasmas, together with their confining potentials. Once this was accomplished transversely directed gas jets would be turned on at the inner part of the expander. Ionization of these jets, either accomplished by the local plasma density, or by external means, such as by the use of microwave beams would lead to their acceleration out through the expander, creating the required K-S effect. The K-S beams could now be turned off.

In addition to the optimization studies described above some estimates were made of the power requirements for the K-S beams as compared to the fusion power output of an axisymmetric tandem-mirror system. To this end an older tandem-mirror engineering design, "MiniMars," a 600 MWe system studied in the 1980's in non-axisymmetric form, was reconfigured as a K-S T-M. It was found that the K-S beam power required for stabilization was smaller than that required to maintain the plugs, which was, in turn, small compared to the fusion power output.

Probably the most significant confirmation of the effectiveness of the K-S in a tandem-mirror context was provided by results from the new tandem-mirror transport code, SYMTRAN. This code models both radial and axial transport in a K-S-T-M, including potential confinement by the plugs and its radial variation. Results from this code included finding the conditions required for D-T plasma ignition and stable "burn," with plasma radii and confining field strengths much lower than those required in a tokamak.

Finally, work was initiated on finding those plasma conditions in the expander that would insure "communication" adequate to avoid the development of so-called "trapped-particle" modes within the region between the plugs and the expander. While some conditions that should insure this stability were derived, it was felt that further work is needed to fully resolve this question. Here the GDT results, where no such modes were observed, stands as an example that the problem can be resolved.

Conclusions

The studies that were performed of the Kinetic Stabilizer Tandem Mirror concept have provided a firm theoretical/computational base for proceeding to experimental verification of the concepts involved. It can already be seen from the results obtained that the K-S T-M offers a new, and a potentially shorter and less costly, approach to achieving a net-power-producing fusion power system, including the demonstration of a stably "burning" DT plasma. Its underlying virtue is that it offers the possibility of magnetically confining a plasma in an essentially turbulence-free state, thereby eliminating many, if not most, of the problems of unpredictability and complexity that turbulence brings with it in closed systems such as the tokamak or the stellarator.

Certainly the results justify a new look at the tandem-mirror concept as a promising alternative line to pursue, in parallel with the tokamak

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